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Composite grid structures can be made to possess outstanding structural properties which can exceed those of laminated and sandwich construction. The superior performance is achieved by avoiding micro-cracking and delamination failures common in the conventional composite structures. The manufacturing processes of grid structures, however, are not available. The goal of the program is to devise novel, automated processes so that cost-effective composite grids can be made. Two general approaches are outlined in this report; viz., TRIG and stacked joint grids. A unique feature of our invention is that these grids can be made using filament winding and pultrusion, two of the most developed processes readily available.

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COMPOSITE GRID STRUCTURES

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Abstract

Composite grid structures feature very attractive stiffness and strength properties along with very low weight. This review includes two proprietary manufacturing processes of grid structures. Tooling reinforced grids with either adhesive bonding or fiber interlacing and grids with stacked joints are described. Examples of applications to spacecraft, rotating machinery, and reinforcement of concrete are discussed. The latest achievements include $\pi/4$ *isogrids and rapid assembly and joining of stacked grids for new concrete columns and repair of existing ones. A micro-mechanics analysis of concrete-filled grids is developed and incorporates the key difference between its tensile and compressive properties. This model provides the design basis of grid reinforced concrete structures patterned after the classical laminated plate theory. Comparison with data measured from beams is also presented.*

1 Introduction

Grid structures are not new; they have been used in civil engineering for many years. The aeronautical industry used metallic grids as early as World War II. The British bomber Vickers Wellington was one of them (Figure 1). Nowadays, modern aircraft such as Airbus A-330 and A-340 have composite grid reinforced skins in their horizontal tails. They are still hand-made! Hence our interest in developing new automatable manufacturing processes.

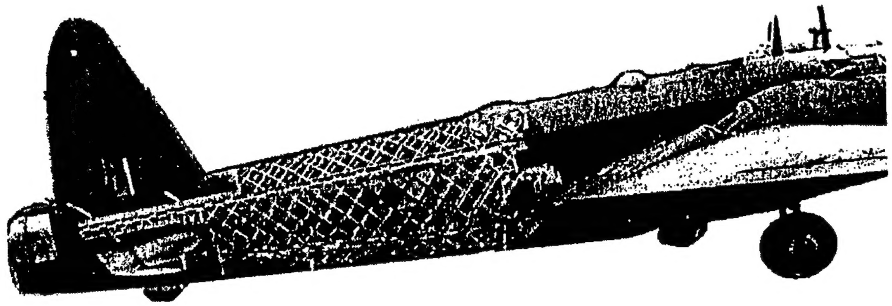

Figure 1: Grid structure in Vickers Wellington (Mk IV) fuselage. Ensures structural toughness as shown after severe anti-aircraft damage

2 Advantages of composite grids

Both composite unidirectional fibers and grids are highly directional material systems, against which metals cannot compete! The behavior of graphite (*Carbon Fiber Reinforced Plastic - CFRP*) and E-glass (*Glass Fiber Reinforced Plastic - GFRP*) composites is shown in Figure 2. Moreover, composite grids are subject to neither micro-cracking nor delamination, to which composite laminates are often prone. Requiring neither complex layup procedures nor debulking nor bagging nor autoclaving, processing costs for grids remain very low. As a matter of fact, very few consumable items are involved.

The three most popular standard grid structures are (Figure 3):

- square grids.
- angle grids.
- isogrids.

Some composite grids are already commercially available (Figure 4).

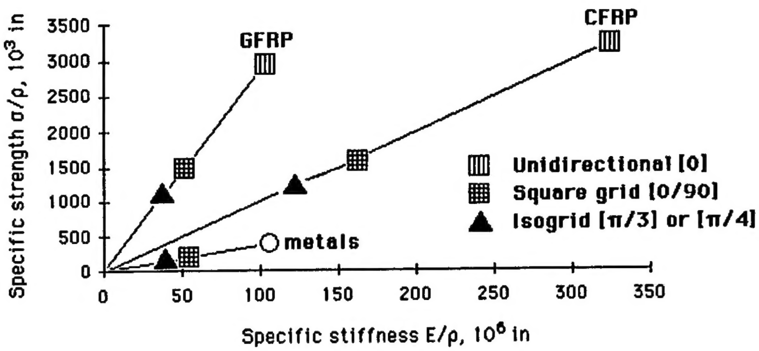

Figure 2: Specific strength and stiffness of composites and metals

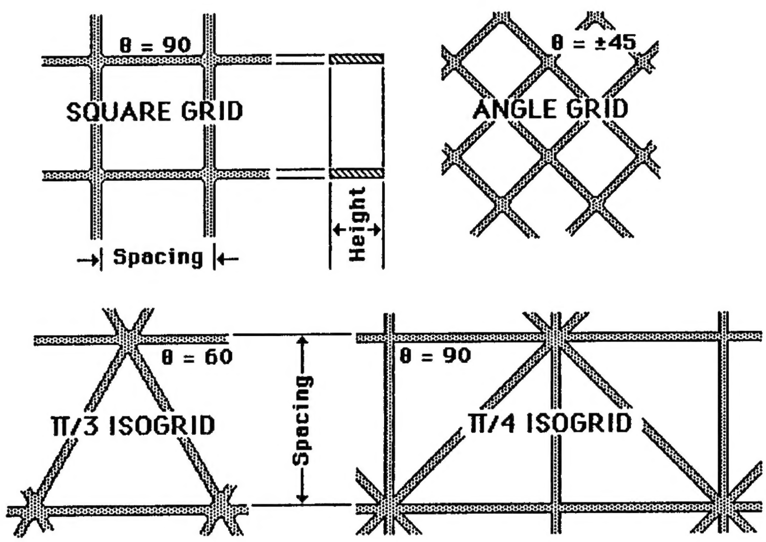

Figure 3: Standard square-, angle-, and iso-grids

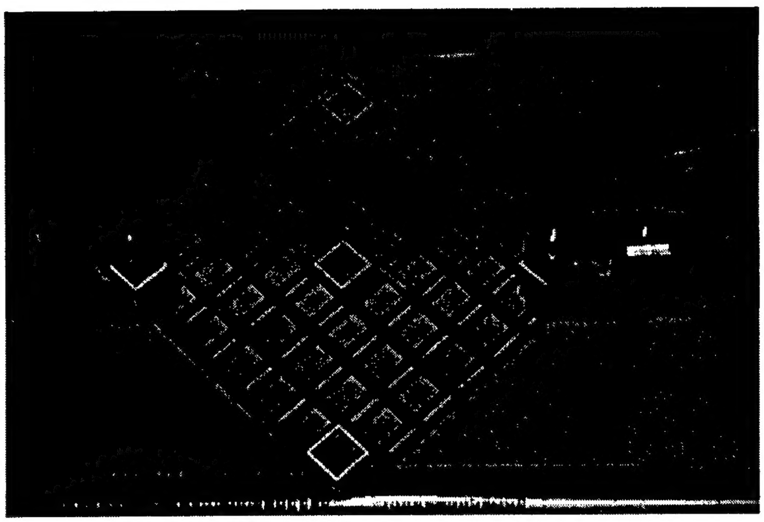

Figure 4: Grating panel made of glass/polyester square grids. Courtesy of Fibergrate, Dallas, TX

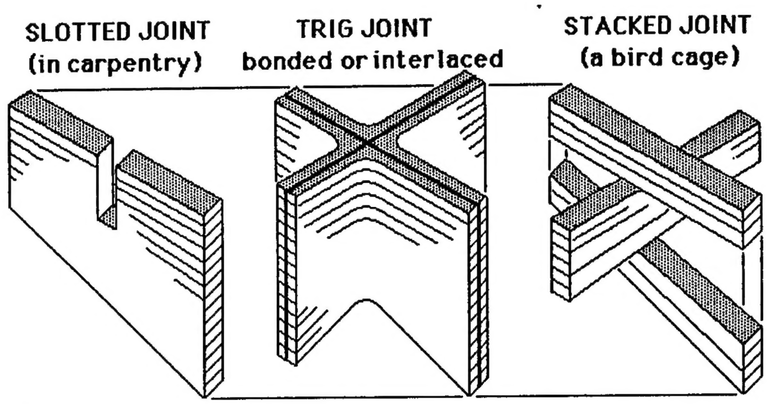

Figure 5: Types of grid assembly joints (slotted, TRIG, stacked)

3 Stanford's manufacturing processes

To date, most grid structures are assembled by carving out slots in the ribs in order to join and lock them; they are referred to as slotted joint grids. Two new manufacturing processes were developped by the Stanford Composites Design Center: Tooling Reinforced Interlaced Grids (TRIG) and Stacked Joint Grids. Manufacturing issues and applications of both processes are discussed below.

3.1 Types of grid joints

Grid components are called ribs. The intersection of such ribs is called a joint or node. As aforementioned, there are many possible designs for such joints: slotted joints, TRIG joints and stacked joints (Figure 5).

3.2 Slotted joint grids

Slotted joint grids (Figure 6) are often found in carpentry and have been applied to composite grids. Difficulties include the optimum tolerance of the cut slots and the bonding to seal the joints. Substantial stress concentrations at the cut-out edges also impair their performance.

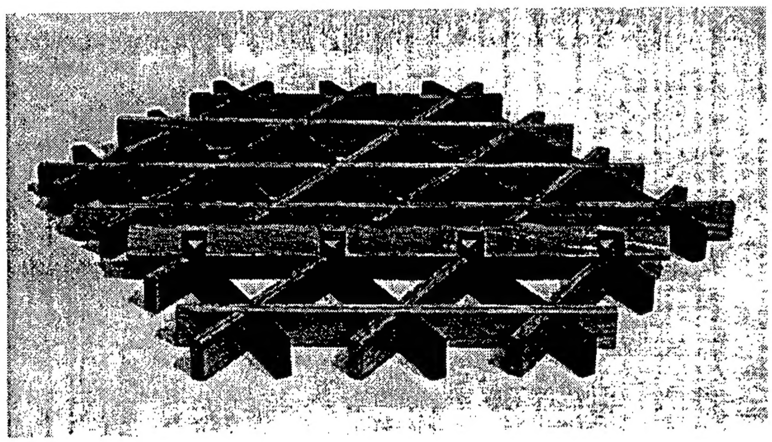

Figure 6: Slotted joint grid structure

3.3 TRIG joint grids

3.3.1 Tooling units

The basic building blocks for TRIG's are rectangular and triangular tubes, with or without a filler (Figures 7 and 8). Their fiber orientations are chosen similarly to those for laminates: typical combinations are $[0], [90], [\pm 45]$. Filled tubes help providing with smooth curvatures when an outer and/or inner skin need to be attached.

These tubes are then sliced to form tooling of appropriate height. The basic shapes are often adapted to yield the requested cross-sections and fiber orientations (Figure 9). Adequate positioning of the sliced tubes allows a wide variety of grid patterns (Figure 10), including [0/90] and $[\pm 45]$ square grids. Diamond-shaped tubes have multiple purposes:

- Helical winding angles other than $[\pm 45]$, such as $[\pm 30]$, for both flat and cylindrical panels.
- Conical shells. In this case, however, the diamond-shaped tubes must have

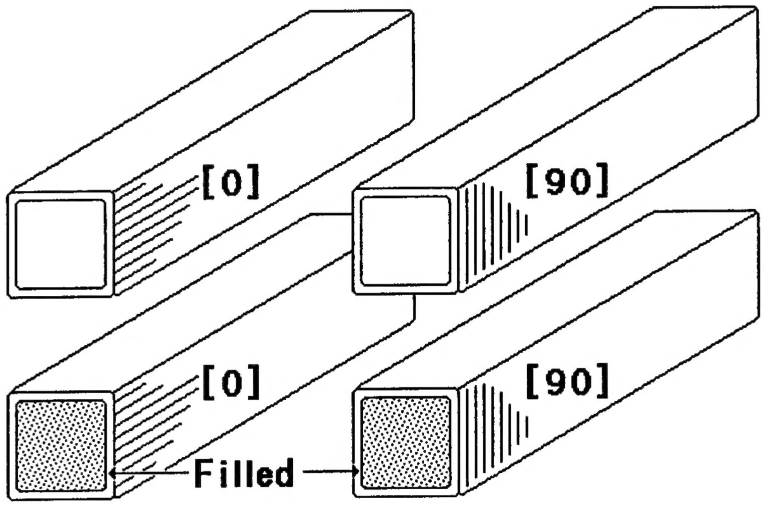

Figure 7: Rectangular tubes used in TRIG's. Hollow (top) or filled (bottom)

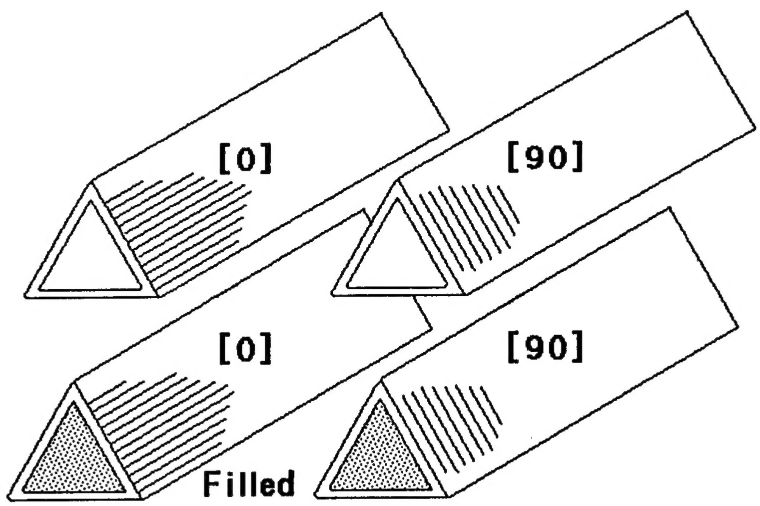

Figure 8: Triangular tubes used in TRIG's. Hollow (top) or filled (bottom)

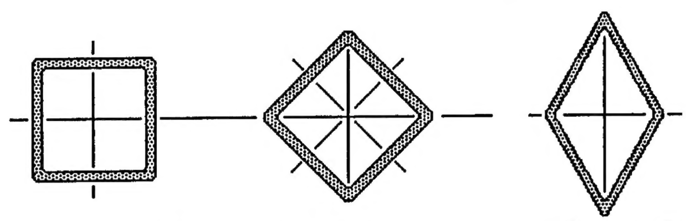

Figure 9: Typical tooling shapes

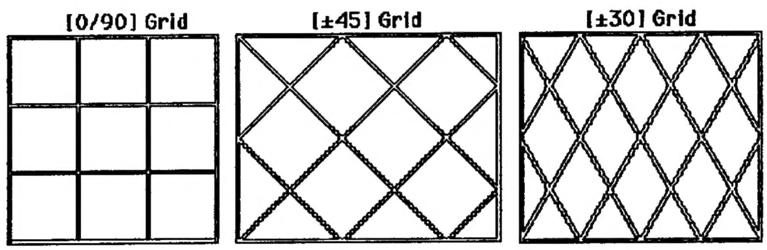

Figure 10: Typical grid patterns using tooling from Figure 9

variable sizes as the diameter of the shell changes.

3.3.2 Tooling consolidation for grids

TRIG processed grids are formed by consolidation of the basic tooling units (Section 3.3.1) with either adhesive bonding or fiber interlaced ribs (Figure 11).

TRIG grids with adhesive bonds

TRIG grids with bonded joints are useful for stiffness controlled applications such as in spacecraft where very low weight and high heat dissipation are crucial. Figure 12 shows a bonded square TRIG grid, to which a skin was subsequently bonded in a separate process.

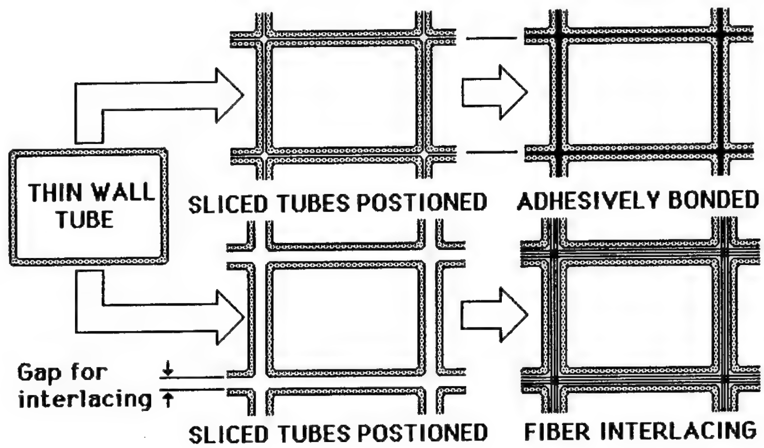

Figure 11: Consolidation of tooling units by adhesive bonding or fiber interlacing

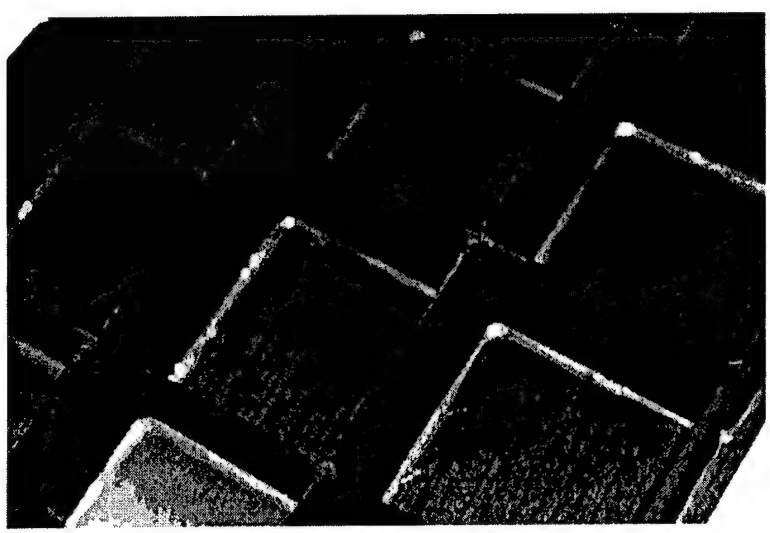

Figure 12: Bonded square TRIG grid, with attached skin panel

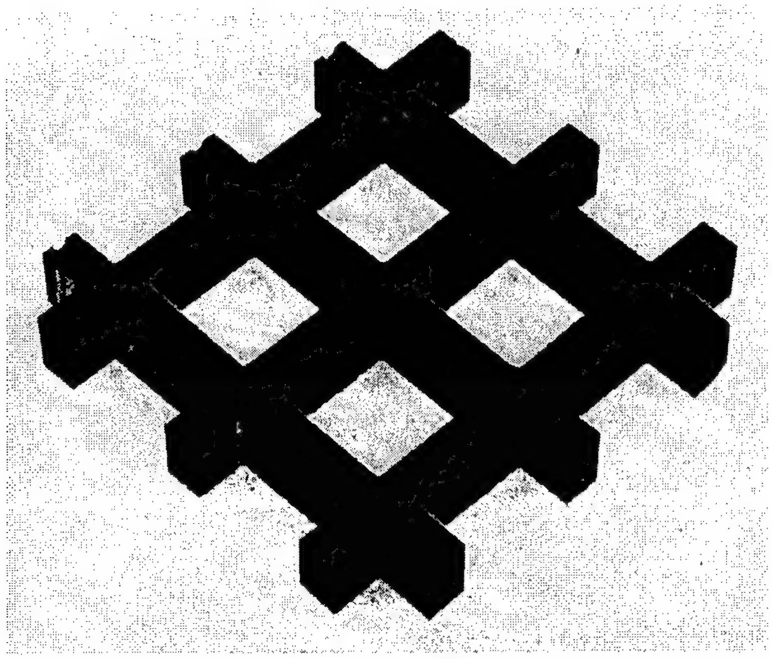

Figure 13: Fiber interlaced square TRIG grid

TRIG grids with fiber interlacing

TRIG grids with fiber interlacing are useful for strength controlled applications including containment rings where ultra high strength is required. Figure 13 shows a fiber interlaced square TRIG grid. It is worthwhile to note that the same square tube is being used in the bonded (Figure 12) and interlaced TRIG's (Figure 13).

Fiber density in TRIG grids

The fiber volume in the ribs of TRIG grids overwhelmingly controls the overall grid properties.

At 50%, fiber density in adhesively bonded grids exceeds that of fiber interlaced grids, usually between 25% and 50% (Figure 14). However, fiber density strongly depending on the manufacturing process used, it can be improved by several means for interlaced grids (Figure 16). Interlaced joint options are:

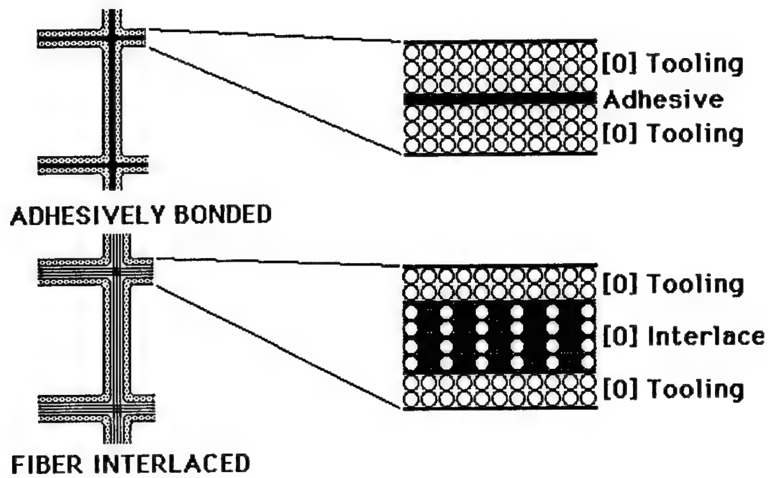

Figure 14: Fiber density in adhesively bonded and fiber interlaced TRIG's

- Standard interlaced joint. So far, Fibergrate (Figure 4) and other companies have often made grids by placing fibers or tows in precut grooves. The fiber volume in such standard ribs is usually lower than 25%.

- TRIG interlaced joint. The density in such joints increases, the fibers of the tooling tubes being present in the final grid.

- Pin Enhanced Geometry (PEG) interlaced joint. This proprietary method, developed at Stanford, spreads the fibers at the rib intersections, called nodes, so that the fiber density in the ribs can remain around the targeted 50% (Figure 15). The fibers approaching a node are thus split into two paths. The split is achieved by a peg placed in the middle of the gap between the tooling. Instead of a single joint that must accomodate all of the intersecting tows, there are now four smaller joint areas. Hence, lower compaction is needed at the nodes to preserve high fiber density in the ribs themselves. This PEG design yields the best stiffness and strength for interlaced TRIG's, 15 msi and 150 ksi respectively (Figure 17). While the properties improve, the cost of

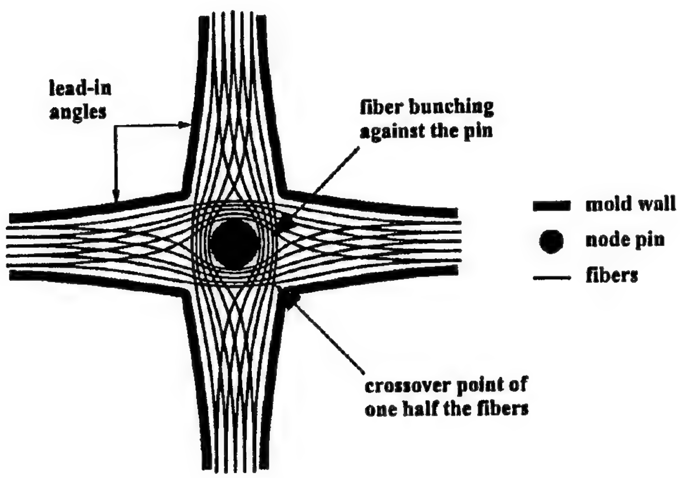

Figure 15: Pin Enhanced Geometry. Splitting of fibers at nodes

manufacturing also increases as compared to other joint designs.

The resulting stiffness and strength properties of the ribs with the various manufacturing methods are shown in Figure 17.

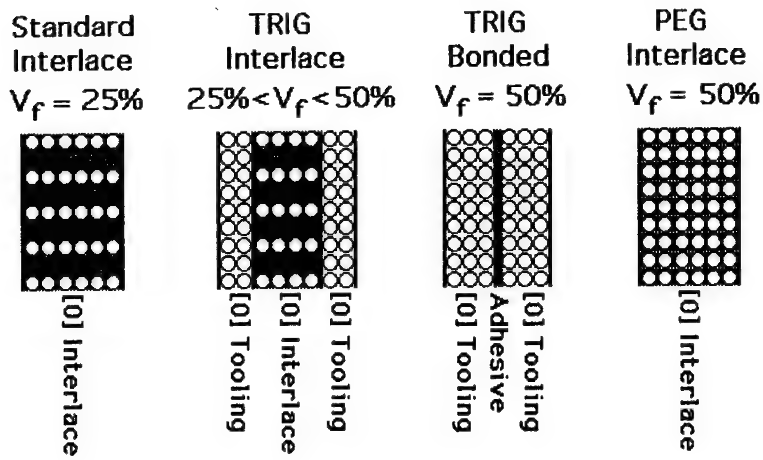

Figure 16: Fiber density in bonded and interlaced TRIG's

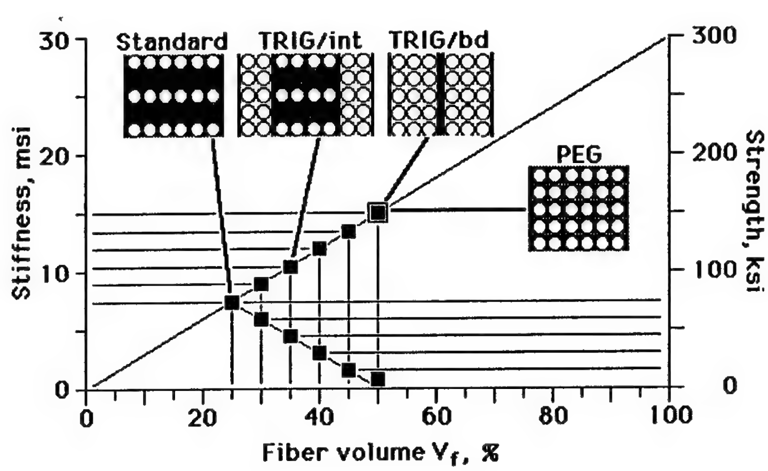

Figure 17: Grid properties for bonded and interlaced TRIG's. The fiber stiffness and strength used in this example are 30 msi and 300 ksi, respectively

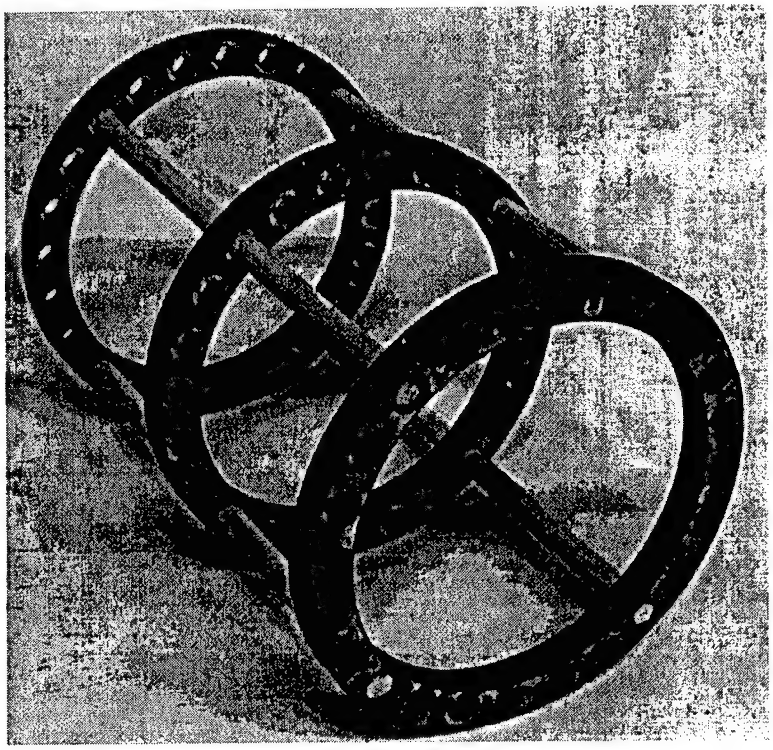

Figure 18: Circs and longis in a stacked joint cylindrical grid. Double circ – single longi (C-L-C) design

3.4 Stacked joint grids

The assembly of stacked joint grids is very quick. This may constitute a tremendous advantage if field assembly is required. Such grids are made of axial rods, called "longis" (L), and peripheral rings, called "circs" (C) (Figure 18).

Grids with stacked joints have the same stiffness and strength as the standard interlaced grids (Section 3.3). The effective fiber volume fraction would be 25%, which would have a rib stiffness of 7.5 msi and strength of 75 ksi for a single circ – single longi (C-L) design; equivalent to a [0/90] laminate.

As expected, the ratio of longi over circ varies with the assembly designs. Common ratios are single longi – double circ (C-L-C) (Figure 20) , equivalent to $[0/90_2]$

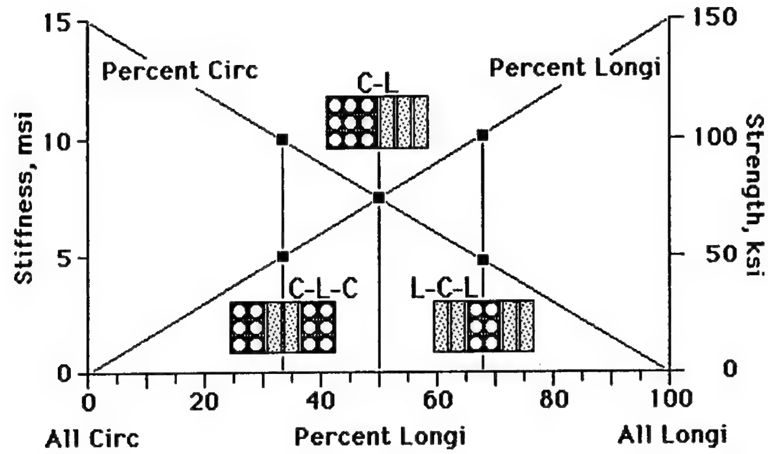

Figure 19: Strength and stiffness of stacked joint grids. Effects of the "circ/longi" ratio

and double longi – single circ (L-C-L), equivalent to $[0_2/90]$. The elastic constants and strength properties naturally change in proportion to the volume ratios of the longis and circs. For instance, the longitudinal stiffness and strength of a single longi – double circ grid (C-L-C) are 5 msi and 50 ksi, respectively; the circumferential stiffness and strength are 10 msi and 100 ksi, respectively (Figure 19).

For cylindrical grids with stacked joints, there are at least 3 simple configurations (Figure 21):

- Single circ – single longi (C-L).
- Double circ – single longi (C-L-C).
- Single circ – double longi (L-C-L).

The choice of a specific configuration depends on the desired structural properties, related to the methods of fabrication and assembly. Another important consideration is the joining method between the longis and the circs. An adhesively bonded joint would be ideal. However, pressure between the adherends is required

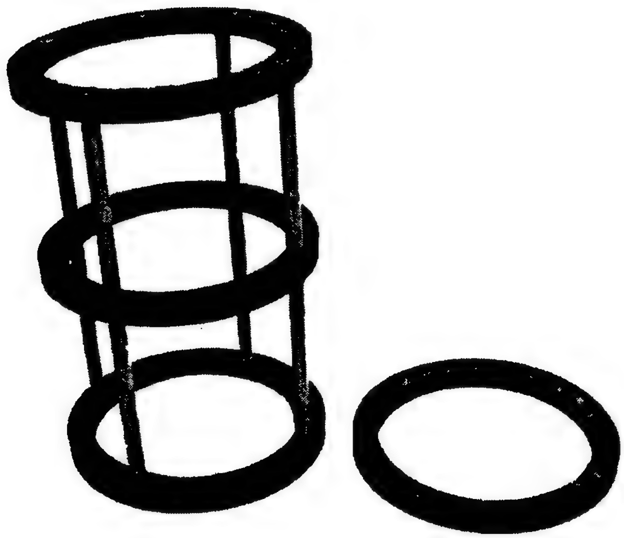

Figure 20: Double circ – single longi (C-L-C) cylindrical grid

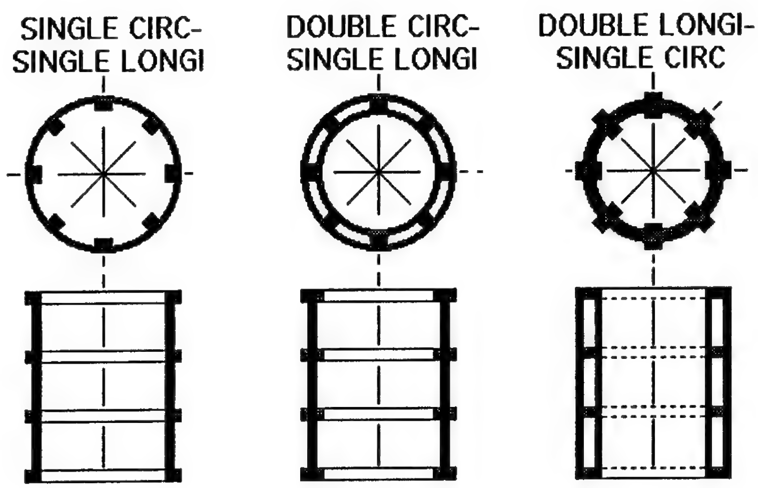

Figure 21: Standard designs for circular cylindrical stacked joint grids

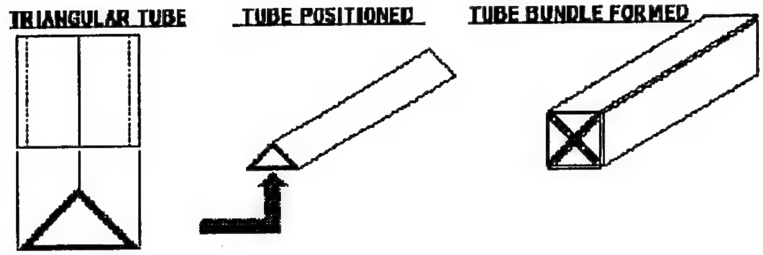

Figure 22: Bundling of triangular tubes for bonded TRIG's

and is not always easily applied. The assembly method will thus depend heavily on the bonding procedure selected.

4 Applications of grids

4.1 TRIG joint composite grids

As described, TRIG structures feature either adhesive bonds or fiber interlacing. Both types enjoy multiple applications.

4.1.1 Bonded TRIG's

Grids without interlacing are built by first bonding a bundle of tubes together and then slicing the bonded bundle. The stiffness of an assembled rib is 15 msi, and the testing measured strength is around 11 ksi.

The manufacturing process is as follows: first, tubes of square or triangular cross-sections are made by filament winding or pultrusion and positioned to form a bundle (Figure 22). Triangular tubes have higher shear rigidity than square tubes. Isosceles triangles are better than equilateral ones if a rectangular outer boundary is required. Once the tubes are positioned, they can be bonded using a vacuum infiltration process, which is an effective method to avoid voids in the bonding process. Slicing of the bonded bundle is a low cost operation to obtain grids with

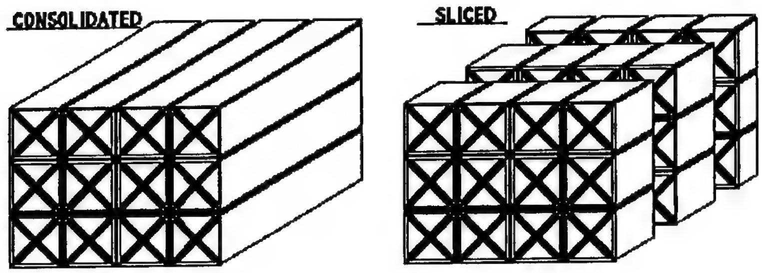

Figure 23: Consolidation and slicing of bundles into a $\pi/4$ isogrid

any desired height or depth (Figure 23). The surface finish is smooth and can have up to 15 msi in stiffness.

Another very important property is that thermal expansions can be zero in both rib directions if graphite/epoxy materials are used. It then gives zero thermal expansion in the entire grid plane. This unique feature cannot be achieved by laminates which can give zero expansion in only one direction.

4.1.2 Interlaced TRIG's

Cylindrical shells

For cylindrical shells, TRIG's are made by first slicing thin wall tubes with the desired curvature so as to conform to that of a finished circular cylindrical shell. The inside radius must conform to the outside radius of the inner shell or mandrel. The slicing operation of the thin wall tube is shown in Figure 24.

Tooling can be positioned following the helical pattern of the filament winding machine, laid down onto the mandrel. The starting pattern is shown as small beads in Figure 25. The precut tooling can then be bonded to the inner shell or mandrel following the helical pattern laid down previously. The final step is to use filament winding to place the interlacing in the gap between the tooling (Figure 26).

The cylinder in Figure 27 is made of a pultruded glass tube for tooling and

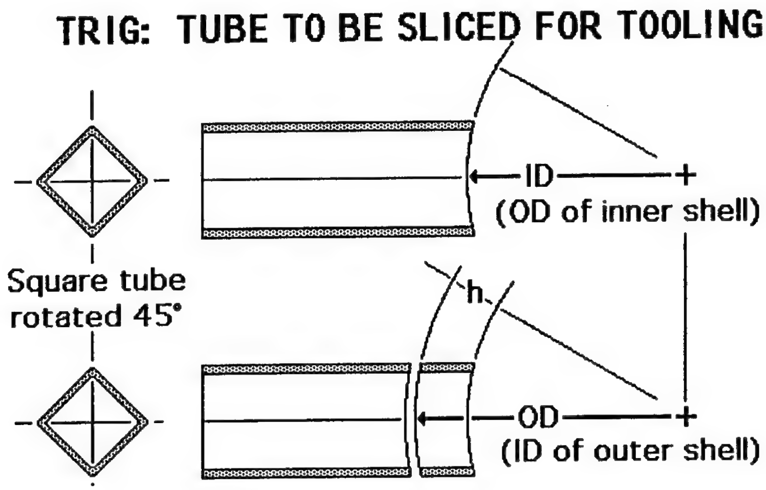

Figure 24: Tooling for cylindrical interlaced TRIG's

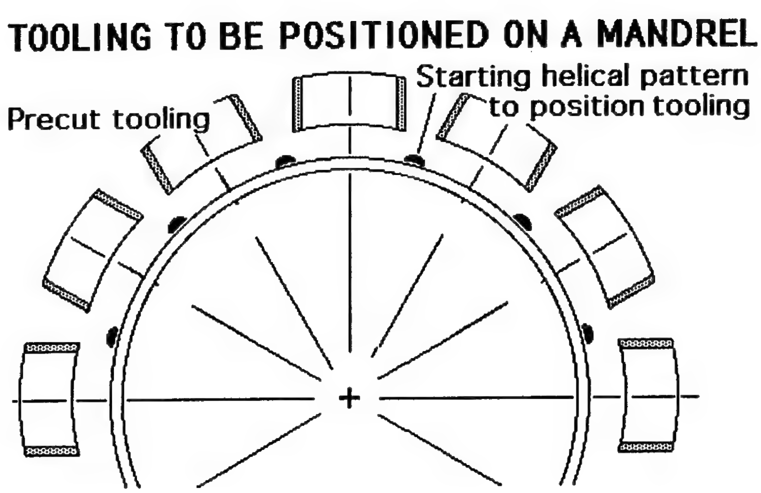

Figure 25: Tooling positioning for cylindrical interlaced TRIG's

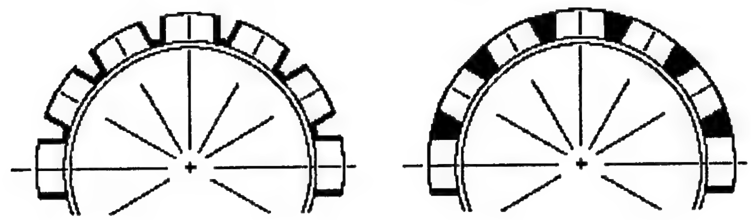

Figure 26: Helical winding process for cylindrical TRIG's

glass/epoxy for interlacing. The gap is flared so that interlacing can be readily placed and provides a self-tightening design that forces the tooling to be bonded to the inner shell or mandrel. The flared gap between tooling is better than the straight gap if the groove is cut in a rigid foam tooling or cast in a soft rubber tooling. As stated earlier, the standard interlacing is limited by the fiber volume fraction of the joint. TRIG is better than the standard interlacing because a balance between stiffness and strength of the rib can be more readily achieved. In addition the ribs are well defined and can have a stiffness of up to 15 msi.

Conical shells

TRIG for conical shells needs trapezoidal or diamond tubes. The sizes of the tubes must change to adjust to the changing diameter of the conical shell (Figure 28).

4.2 Stacked joint composite grids

4.2.1 Cylindrical shells

Besides circular grids, square and rectangular grids can also be assembled. Terminology is identical. As already stated, the specific configuration desired is a function of the properties required and the method of assembly. For square and rectangular cross-sections (Figure 29), the double circ configuration (Figure 30) is recommended

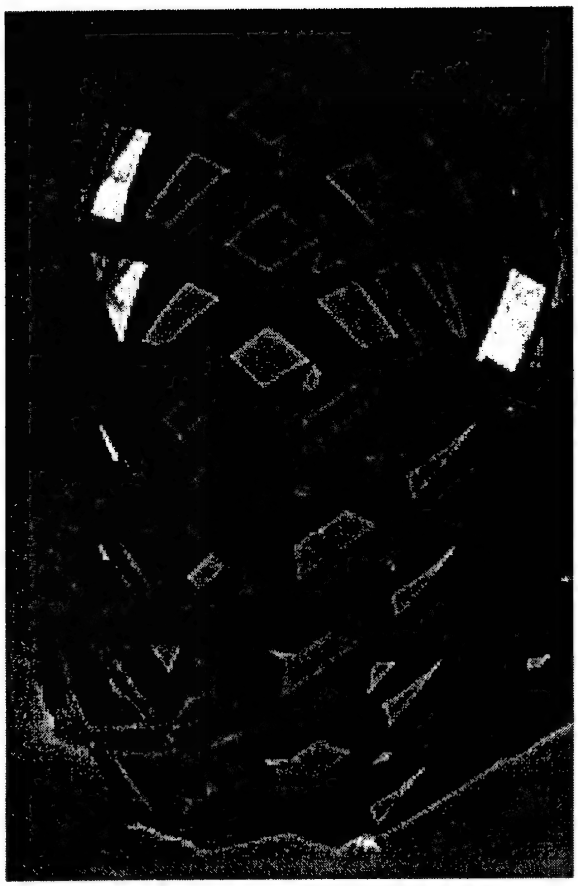

Figure 27: Cylindrical interlaced TRIG

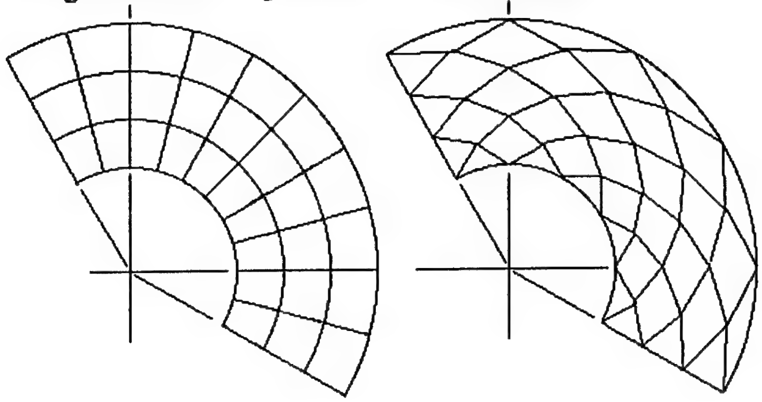

Figure 28: Conical interlaced shells

if flexural rigidity in the circumferential direction is needed. This would be the case when using grids as reinforcements for square and rectangular concrete columns. The single circ configuration may be inadequate in its bending resistance.

4.2.2 Conical shells

For conical shells, grids with stacked joints may also be easily manufactured and assembled (Figure 31). The same considerations given to the straight cylinders must be similarly applied. The method of assembly is again dictated by the bonding procedure of the stacked joints.

4.2.3 Spherical and ellipsoidal shells

Spherical and ellipsoidal heads and shells can also be made using TRIG with stacked joints. Two examples, based on the single longi – single circ design, are shown in Figure 32. The degree of complexity for shells and heads increases significantly over that for circular cylinders. Having double curvatures within the shell elements is one source of difficulty. The surfaces to be bonded must have the same curvatures to provide intimate contacts for bonding.

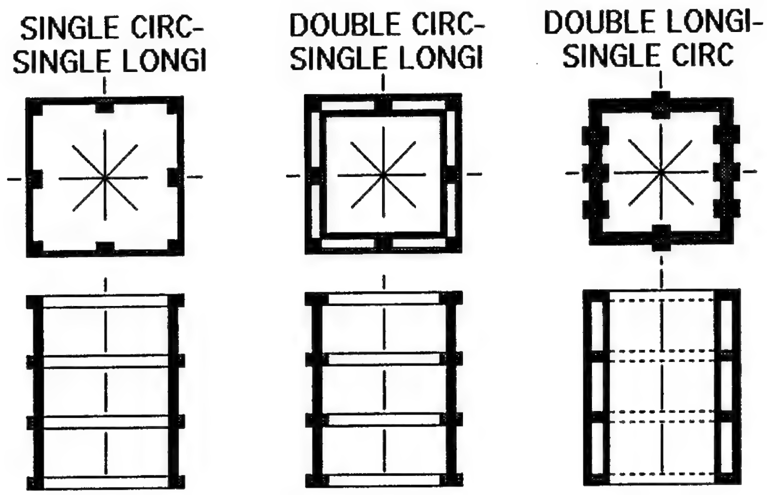

Figure 29: Standard designs for rectangular cylindrical stacked joint grids

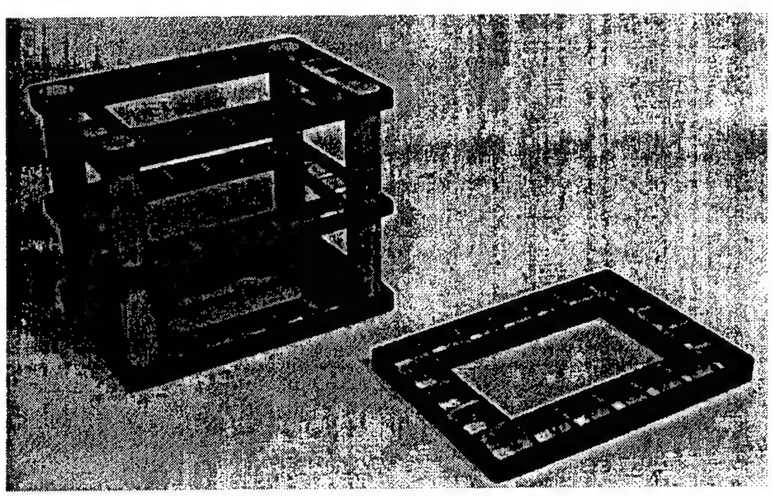

Figure 30: Double circ – single longi rectangular cylindrical grid

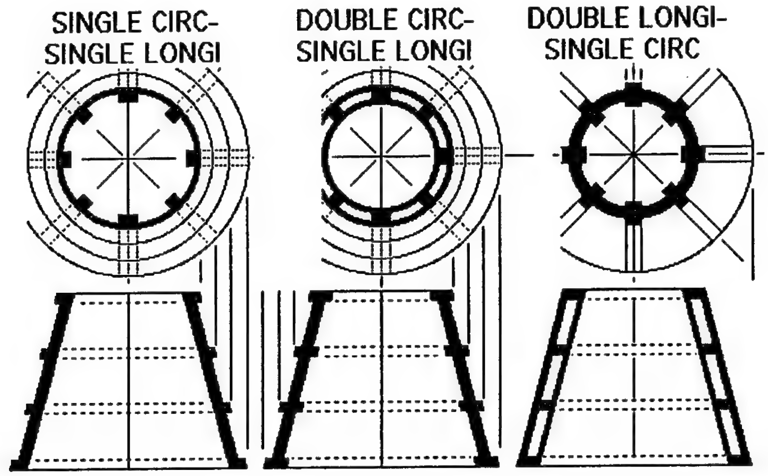

Figure 31: Standard designs for conical stacked joint grids

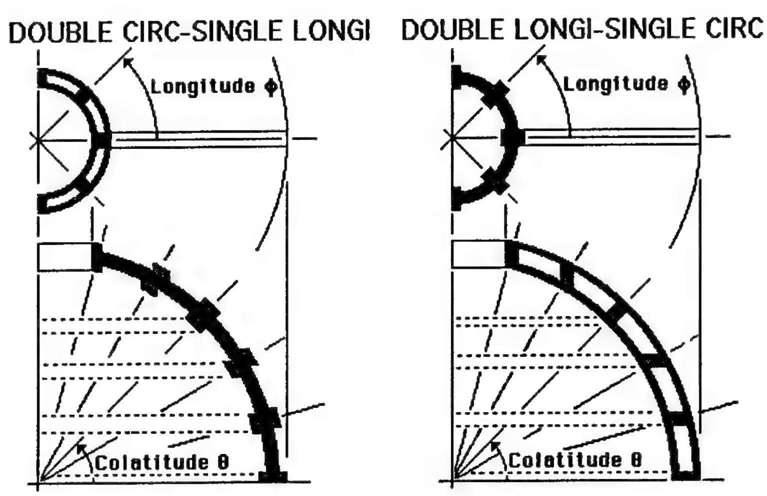

Figure 32: Standard designs for spherical stacked joint grids

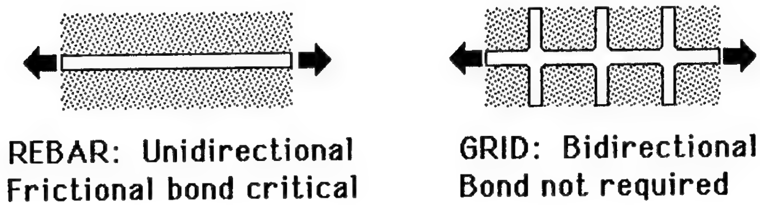

Figure 33: Steel rebars vs composite grids as concrete reinforcement

5 Composite grid reinforced concrete

Composite grids are an effective reinforcement for concrete structures because of a strong synergistic effect. A composite grid having concrete as a filler can be labeled as a "compcrete" in which

- the grid holds the concrete in place and gives a tensile strength capability,
- the concrete filler gives the "compcrete" shear rigidity and prevents the rib from buckling,
- unlike the friction force between conventional steel rebars and concrete, grids provide two-dimensional reinforcement without any interfacial bonding. The transfer of forces is affected by the interlocked network between the grid and the concrete filler (Figure 33).

Thus, grids reinforce concrete and concrete reinforces grids. This reinforcement is mutual.

5.1 Properties of compcrete

Test data of a "compcrete" layer (0.5" thick) show that the concrete filler does not pop out from the surrounding grid when the layer is tested in tension, compression, bending and twisting. Unlike ice cubes that pop from an ice tray when it is twisted,

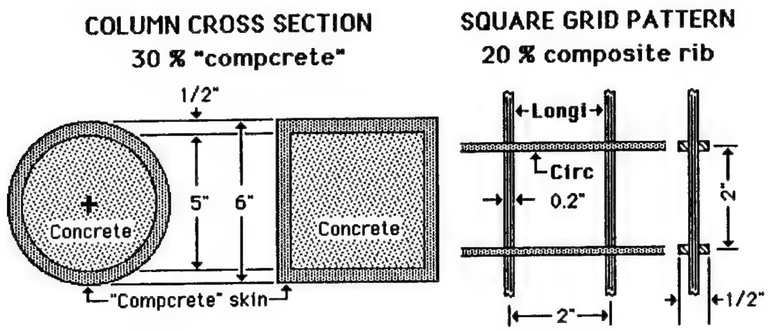

Figure 34: Compcrete cross-section

the concrete filler remains locked in up to an applied strain of 1%. In addition, the "compcrete" layer is resilient; i.e., exhibits some hysteresis upon loading, unloading and reloading but shows no significant permanent strain.

5.2 Applications of compcrete

It is therefore our plan to utilize this "compcrete" layer for the containment of concrete structures. It is rationalized that if a concrete structure is prevented from spallation by having a "compcrete" layer on the outside, the structure can be resistant to static and seismic loads (Figures 35 and 36). Proposed test specimens of circular and square cross sections are shown in Figure 34. The amount of composite required for this reinforcing scheme is small compared with the total volume of the concrete structure. In Figure 34, the outer layer of 0.5" represents only 30% of the volume of the structure. Of this layer, only 20% is made of composite grid. Thus the volume fraction of composite grid is only $0.3 * 0.2 = 0.06$ or 6% by volume which is below 4% by weight. This percentage will further reduce if the rib spacing in the grid is increased to 3", in which case the new volume fraction will be 4%, a reduction from 6%; the weight fraction will be 2.6%. It is important to keep the use of grids to a minimum: that lowers of course the cost.

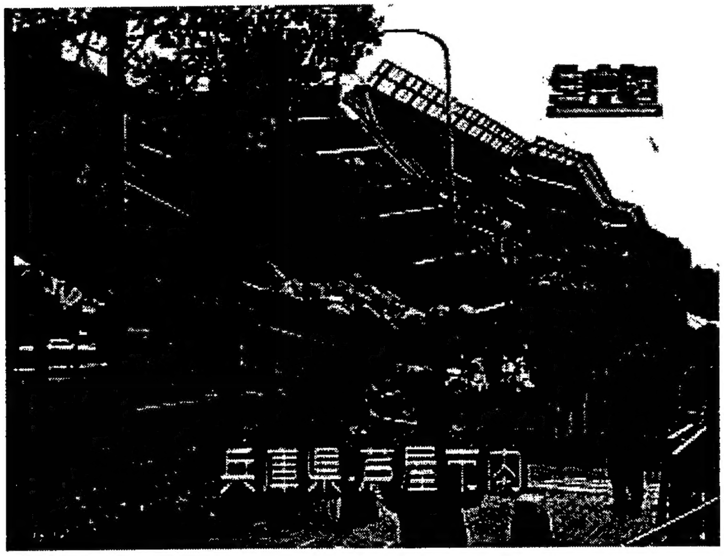

Figure 35: Collapse of an unsupported steel rebar framework. Kobe, Japan. January 17, 1995

5.3 Bi-modulus behavior of compcrete

Another unique feature of the "compcrete" layer (Figure 37) is the difference between its tensile and compressive stiffness. Our test data show that the tensile stiffness is 0.5 msi and the compressive stiffness, 1.2 msi, nearly three times the tensile one.

Under a uniaxial tensile load, the composite grid separates from the concrete filler along the rib transverse to the load. This is shown as a gap (Figure 38), which is analogous to a micro-crack in a cross-ply laminate subject to a tensile load. Both the concrete filler and the ribs transverse to the load further restrict Poisson's contraction. There is no gap along this transverse direction. The tensile modulus is equal to that of the ribs corrected by the rib volume fraction; e.g., if the rib modulus is 5 msi and its volume is 10%, the effective tensile modulus is 0.5 msi. Poisson's coefficient is then near zero.

Figure 36: Collapse of an unsupported steel rebar column. Concrete broke away and steel rebars buckled. Kobe, Japan. January 17, 1995

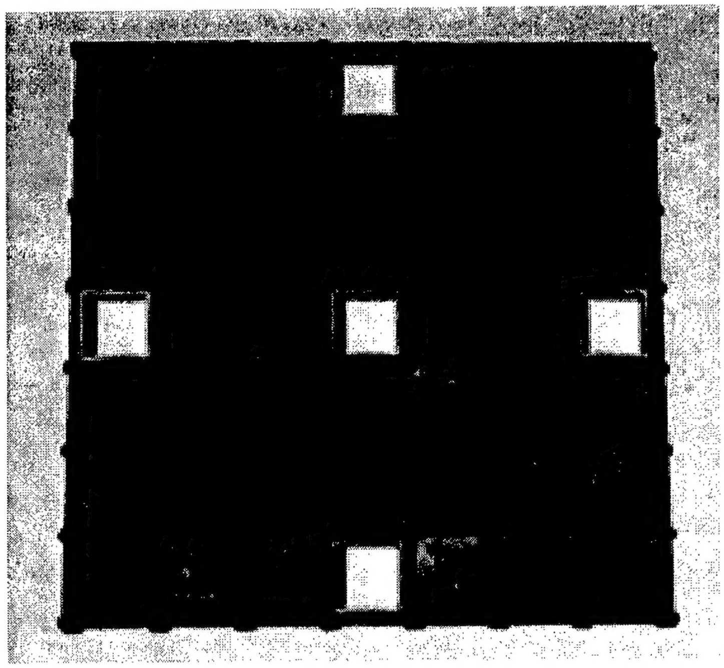

Figure 37: Compcrete layer. Square grid with concrete filler, made by Fibergrate, Dallas, TX

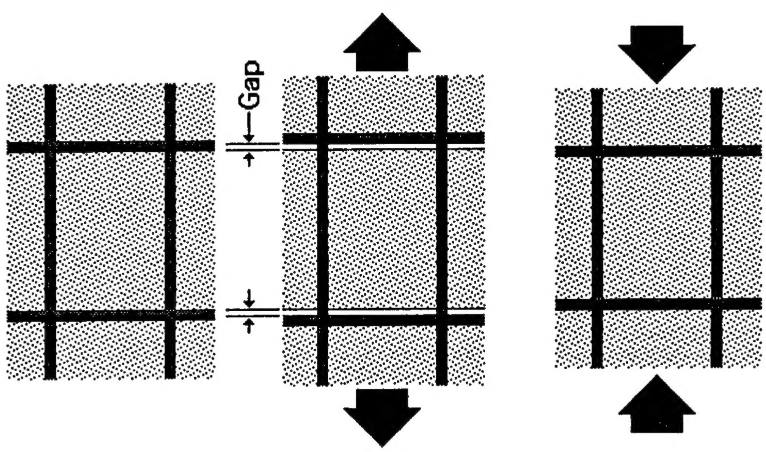

Figure 38: Gap effects in compcrete unidirectional loadings

Under uniaxial compression, there should not be any separation between the ribs and the concrete filler. The compressive stiffness obeys the rule of mixture prediction of the composite ribs and concrete; e.g., if we assume again that the rib modulus is 5 msi and the concrete's, 0.5 msi, and that the volume fraction of the rib is 10%, the effective compressive modulus is $5 * 0.1 + 0.5 * 0.9 = 0.95$ msi, or almost twice the tensile modulus. The compressive Poisson's ratio obeys the same rule of mixtures. Since concrete's Poisson's ratio is less than 0.2, the compressive Poisson's coefficient of "compcrete" is $0.3 * 0.1 + 0.2 * 0.9 \cong 0.2$ or less.

This crucial bi-modulus material behavior must be included in the analysis of test data, even for the bending of beams.

6 Conclusion

The properties of composite grid structures, as either standalones or embedded reinforcements, are very promising. Appropriate manufacturing processes dramatically improve strength and stiffness properties of such grids.

The numerous applications presented in this article are only a few. Almost any domain of engineering can benefit from this new and enhanced utilization of composites.

7 Acknowledgments

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